REVIEW: ACOUSTIC EMISSION TECHNIQUE - OPPORTUNITIES, CHALLENGES AND CURRENT WORK AT QUT

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Abstract: Acoustic emission (AE) is the phenomenon where high frequency stress waves are generated by rapid release of energy within a material by sources such as crack initiation or growth. AE technique involves recording these stress waves by means of sensors placed on the surface and subsequent analysis of the recorded signals to gather information such as the nature and location of the source. AE is one of the several non-destructive testing (NDT) techniques currently used for structural health monitoring (SHM) of civil, mechanical and aerospace structures. Some of its advantages include ability to provide continuous in-situ monitoring and high sensitivity to crack activity. Despite these advantages, several challenges still exist in successful application of AE monitoring. Accurate localization of AE sources, discrimination between genuine AE sources and spurious noise sources and damage quantification for severity assessment are some of the important issues in AE testing and will be discussed in this paper. Various data analysis and processing approaches will be applied to manage those issues.

Key words: Structural health monitoring, acoustic emissions, source localization, source discrimination, severity assessment.

1 INTRODUCTION

Civil infrastructure such as bridges and mechanical structures such as engines need an effective monitoring tool to ensure their safety and reliability. Acoustic emission (AE) technique is one of the several diagnostic techniques used for structural health monitoring (SHM) applications. AE is the phenomenon where high frequency stress waves are generated by rapid release of energy within a material. Common sources of AE in materials include initiation/growth of cracks, material dislocations, yielding and in case of composites, failure of bonds and fibre failure. AE technique involves recording the stress waves by means of sensors placed on the surface of the structure and subsequent analysis of the recorded signals to locate and gather information about the nature of the source of emission (Holford & Lark, 2005). Though AE is generally used as a local technique for monitoring specific areas of a structure, for example regions with visible presence of cracks or crack prone areas such as welded regions and joints with bolted connection; it can also be used for global or semi-global monitoring technique. Fig. 01 below presents a diagrammatic representation of AE phenomenon.

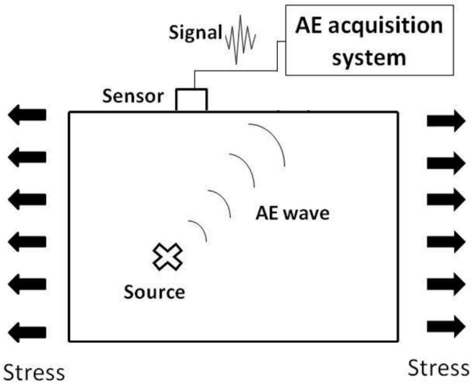


FIGURE 01: AE phenomenon

A simplified representation of AE signal along with commonly used parameters is shown in Fig. 02 adjacent. A local material change giving rise to acoustic emission is known as *event* (Physical Acoustics Corporation, 2007) and if the event AE signal captured by sensor exceeds a set threshold value it is recorded by the data acquisition system and is known as a *hit*. Threshold value is set in order to remove lower level noises and is often dependent upon experimental conditions.

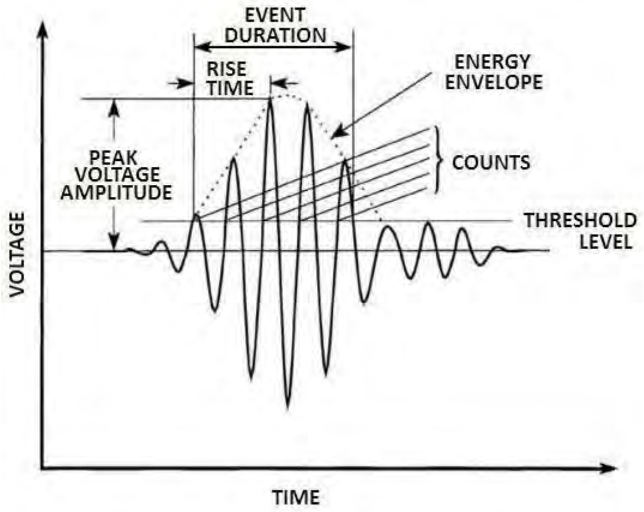


FIGURE 02: Typical AE signal

For analysis purposes the five most commonly used AE signal parameters of a hit (see Fig. 02) are *amplitude*, *counts*, *duration*, *rise time* and *measured area under the rectified signal envelope* (MARSE), also known as *signal strength* (Pollock, 1989). Amplitude is the highest peak voltage reached by an AE signal waveform. Counts are the number of times an AE signal exceeds the threshold value. Rise time is the time between first threshold crossing and the peak amplitude while duration is the time between first and last threshold crossings.

Initial studies on AE phenomenon were made by Kaiser in 1950s using tensile tests. Earliest use of AE technique was in testing of rocket-motor casings in 1964, followed by the applications in areas, such as petrochemical, nuclear, aerospace and construction industries (Scruby, 1987). First application of AE technique to monitor bridges was reported in early 1970s and, later in the decade US Federal Highway Administration undertook more tests. More information about the early tests can be found in (Holford & Lark, 2005; Lozev, Clemena, Duke Jr., Sison Jr., & Horne, 1997). Nowadays, AE technique is routinely used to monitor pressure vessels, aerospace structures, rotating machinery, tool wear, pipes and weld analysis. It has been successfully applied for a wide range of materials, such as metals, concrete, composites, wood and rocks.

2 OPPORTUNITIES AND CHALLENGES

2.1 **Advantages and comparison with other SHM methods**

One of the common and simplest forms of SHM methods is visual inspection where trained personnel inspect structures in regular intervals to check the presence of any signs of damage and recommend appropriate retrofitting if necessary. This is simple and the use of dye penetrant can facilitate inspection; but it may be hard to locate small or hidden cracks. Also, cracks due to corrosion or fatigue may go undetected until they reach critical stage (Holford, Davies, Pullin, & Carter, 2001). In tap test, surface of a structure is tapped with a small hammer and the response is compared to that from a known good area (Chang & Liu, 2003). Although tapping is simple and mechanical hammers have been developed with sound analyser to aid in detection, it can be time consuming and tedious when used to monitor large area. Vibration monitoring techniques are popular global monitoring tools and based on the principles that changes in the global properties (mass, stiffness and damping) of a structure cause a change in its modal properties (such as natural frequencies and mode shapes). The modal properties or the quantities derived from them such as modal flexibility and modal strain energy, can be used for damage identification (Farrar, Doebling, & Nix, 2001; Shih, Thambiratnam, & Chan, 2009). However, in large sized structures, some damage may only cause negligible change in dynamic properties and thus may go unnoticed. In ultrasonic method, transducers are used to introduce high frequency waves into a specimen and receive the pulses. If inhomogeneities are present in the material, changes to the propagating waves are induced (Mancini, Tumino, & Gaudenzi, 2006). Though position of flaw can be determined, ultrasonic method is expensive and coupling of sensors with the specimen surface may create problem.

Compared to the above methods, AE possesses some distinct advantages. It is a passive technology; in sense that no external energy needs to be supplied but energy arising from within a structure is utilized. AE technique enables real time monitoring of a structure as signals originate as soon as damage occurs. AE technique is highly sensitive, so even smallest defects can be detected. Non-interference with normal activity of the structure is another benefit, for example, when a bridge is monitored using AE technique it does not need to be shut to traffic or pedestrians.

2.2 **Challenges**

Despite the advantages, successful use of AE technique for structural health monitoring applications has several challenges. Due to high sampling rate needed for data capture, large amount of data is usually generated during AE testing. Hence an effective data analysis strategy is necessary, especially for real time long term monitoring uses as data storage and transmission becomes important. Three issues are closely associated with data management and processing and will be discussed next.

2.2.1 Accurate localization of AE sources

One of the major challenges in AE technique and an active area of research is the analysis of recorded AE signals to accurately locate the sources of emission. Source location is usually carried out using the popular time of arrival (TOA) method, where the differences in arrival times of signals at different sensors and velocity of the waves are used to find the location of the source using triangulation techniques (Nivesrangsan, Steel, & Reuben, 2007; Tobias, 1976). Complications may arise as AE waves may travel in various forms such as P-waves (primary/ longitudinal/pressure waves), S-waves (shear/ transverse waves) and Rayleigh (surface) waves as well as reflected and diffracted waves (Ohtsu, 1996), see Fig. 03. P and S waves, also known as bulk waves, travel in the bulk of material (that is, in a infinite medium), whereas Rayleigh waves arise due to the interaction of longitudinal and shear waves and travel on the surface of a semi-infinite solid (Rose, 1999). In plate like structures, Lamb waves are common form of propagation (Holford et al., 2001). Lamb waves are different from bulk waves as they can travel in a variety of modes with different group and phase velocities.

It is necessary to identify the modes recorded by sensors and use their velocities to calculate source locations accurately.

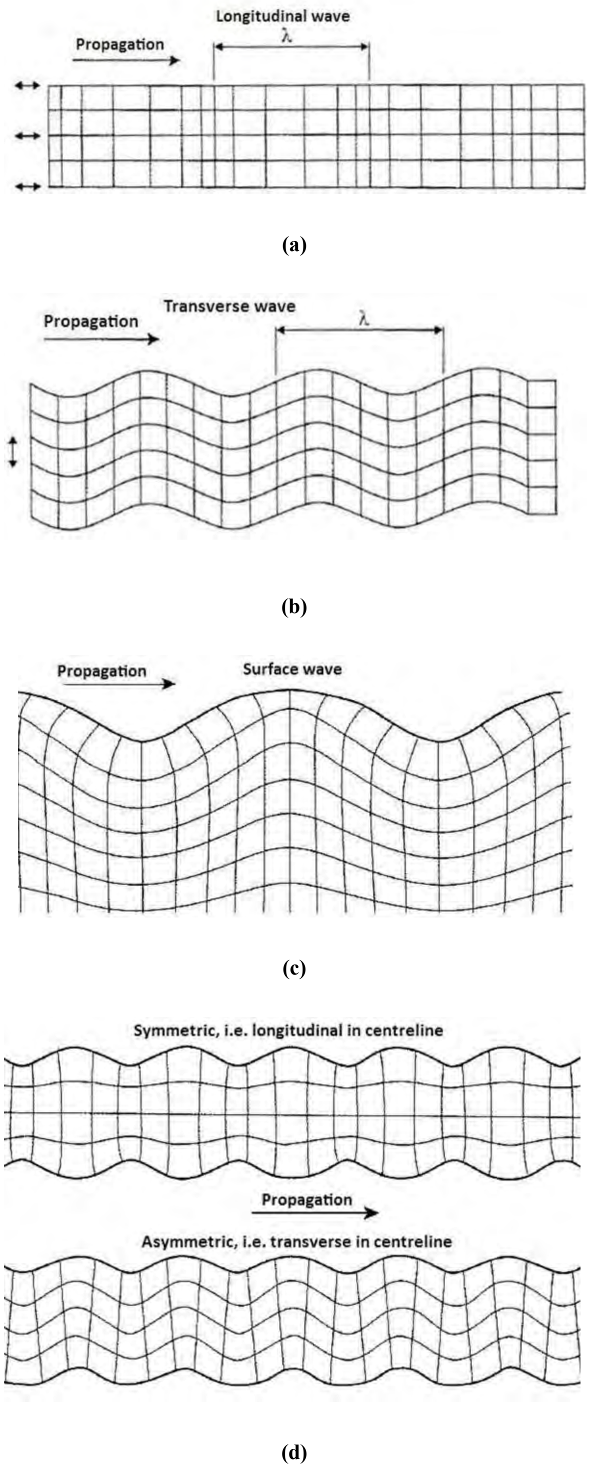


FIGURE 03: Travel modes of AE waves: a) Longitudinal, b)Shear, c) Surface, d) Lamb waves (symmetric and asymmetric) (Holford & Lark, 2005)

2.2.2 Source identification

During AE testing, the volume of data is further increased as a number of spurious sources can also produce AE signals which then can mask genuine damage related signals. In bridge monitoring applications large amount of signals have been found to come from erroneous sources (sources other than cracks) (Gong, Nyborg, & Oommen, 1992; Hamstad & McColskey, 1999). Hence, it is important to accurately and automatically sort extraneous acoustic emission from crack based acoustic emission (Hamstad & McColskey, 1999).

The use of AE signal parameters such as amplitude, duration, rise time and energy content (see Fig. 02) is the simplest data analysis approach. Several previous studies have attempted to use parameters based approach in order to distinguish signals from various sources. For example, in study of crack growth in steel bridge hanger, mechanical and fretting noises were found have longer duration and longer rise times compared to crack signals (Sison, Duke Jr., Lozev, & Clemena, 1998). Parameter based approach is simple but has several drawbacks. For example, use of parameters alone is unable to distinguish between the actual sound wave produced by a fracture event and the reflections of that wave from the edges of propagating medium (Morscher, 1999) and also can misclassify acoustic emission events (Hamstad & McColskey, 1999).

With the availability of advanced computing resources and data storage and transmission capability, recording and analysis of the complete signal waveforms is becoming the preferred analysis approach. Though the signals captured by sensors are affected by the medium of propagation (shape, size and material property) and the sensor characteristics (its type and the way it is coupled to the structure), the signals still contain information about the nature of the source (Grosse, Finck, Kurz, & Reinhardt, 2004). Hence, the waveform based analysis approach is believed to be better than traditional parameter based approach in source discrimination.

To analyse the recorded waveforms, frequency analysis of signals by means of Fourier transform is a popular tool. However, it has some drawbacks, such as loss of information about time of occurrence of different frequency components and its unsuitability for non-stationary signals like AE (Li, 2002; Peng & Chu, 2004). More useful tools for simultaneous frequency-time analysis representation include short time Fourier transform (STFT) and wavelet analysis. STFT involves multiplying a signal with a short window function and calculating the Fourier transform of the product. The window is then moved to a new position and the calculation is repeated. This gives both time-frequency information of the whole signal, but the use of constant window length gives fixed resolution in both time and frequency domains. Compared to fixed length window size of STFT, wavelet analysis uses windowing technique with variable sizes - long time interval windows are used where more precise low-frequency information is needed, and shorter regions are used where high-frequency information is desired (MathWorks Inc., 2009). Wavelet analysis, thus, breaks a signal into different levels, where each level is associated with a certain band of frequencies in the signals.

In studies of composites, different damage mechanisms, such as matrix cracking, fibre debonding and fibre breaking have been found to emit AE signals in different frequency bands (Huguet, Godin, Gaertner, Salmon, & Villard, 2002). Similarly, frequency spectra analysis of AE signals was found to help in distinguishing different chemical systems producing those signals (Wentzell & Wade, 1989). Hence, energy distribution in different frequency bands can be calculated from time-frequency representation of the signal and then be used as source identification and discrimination tool. Ratios of energy distribution in different frequency bands from wavelet analysis has been used to identify different potential failure modes in composites (Qi, 2000).

Search for similarity among signals also helps in source discrimination, as similar source mechanisms emit similar signals if effects due the path of propagation and recording sensor characteristics are negligible. Cross-correlation coefficients in time domain and magnitude squared coherence (MSC) in frequency domain can be used to check if signals are similar or not (Eaton et al., 2009; Grosse et al., 2004; Kurz, Finck, Grosse, & Reinhardt, 2004). Similarity analysis provides a simple way to cluster recorded signals into different groups. This approach is popular in seismic studies, where similarity in earthquake signals are used to gain further insight into source mechanism (Maurer & Deichmann, 1995).

2.2.3 Severity assessment

Another major challenge is the quantification of damage level by analysis of recorded data. This will help assess the severity of the sources. The *b-value analysis* and *intensity analysis* using severity and historic indices are some of the encouraging methods. These will be discussed and applied for analysis of laboratory experimental data in present work.

b-value analysis

The b-value analysis takes analogy from seismology, where events of larger magnitude occur less frequently than events of smaller magnitude – the relationship being expressed by Gutenberg-Richter formula as (Carpinteri, Lacidogna, & Niccolini, 2006; Colombo, Main, & Forde, 2003):

$$\log_{10} N = a - b\, M_L \tag{1}$$

where, M_L = Richter magnitude of the events, N = the number of events with magnitudes in the range $M_L \pm \Delta M/2$, and a and b are empirical constants. The above formula is modified for AE technique and can be written as:

$$\log_{10} N = a - b'\, A_{dB} \tag{2}$$

A_{dB}, the peak amplitude of the AE events in decibels, can be expressed as:

$$A_{dB} = 10\log_{10} A_{\max}^2 = 20\log_{10} A_{\max} \tag{3}$$

b-value is then expressed as:

$$b = 20b' \tag{4}$$

b-value is thus calculated as the slope of log-linear plot of the frequency-magnitude distribution of AE and has been found to change during different stages of damage, for example when microcracks occur in the early stages of damage, the b-value is high but becomes low when macrocracks begin to occur (Colombo et al., 2003). This fact makes the b-value a likely candidate to judge damage progress (Carpinteri, Lacidogna, & Puzzi, 2009).

Intensity analysis using the historic and severity indices

The historic index is defined as a measure of the change in signal strength throughout the test (Golaski, Gebski & Ono, 2002; Nair & Cai, 2010). It aims to compare the signal strength of the most recent hits to all the hits, and is calculated as follows (Gostautas, Ramirez, Peterman & Meggers, 2005):

$$H(I) = \frac{N}{N-K} \cdot \left(\frac{\sum_{i=K+1}^{N} S_{oi}}{\sum_{i=1}^{N} S_{oi}} \right) \tag{5}$$

Similarly, the severity index is the average signal strength for a certain number of events having the largest value of signal strength (Gostautas et al., 2005). It is calculated as follows:

$$S_r = \frac{1}{J} \cdot \left(\sum_{m=1}^{J} S_{om} \right) \tag{6}$$

In (5) and (6), *H(I)* is the historic index at time t, N = number of hits up to and including time (t), K, J = empirically derived constant based on material type, S_{oi} = signal strength of the i^{th} event. K values for metals depend on N and are given in (Nair & Cai, 2010). The maximum values of historic index and severity index are then plotted on an intensity chart divided into zones of damage and the location of the point in the chart will indicate the level of damage. The intensity charts have been developed for metal piping systems (see Fig. 04) with regions marked from A to E with increasing intensity levels and recommended actions ranging from no follow-up needed to major defect requiring immediate shut-down and follow-up inspection (Gostautas et al., 2005).

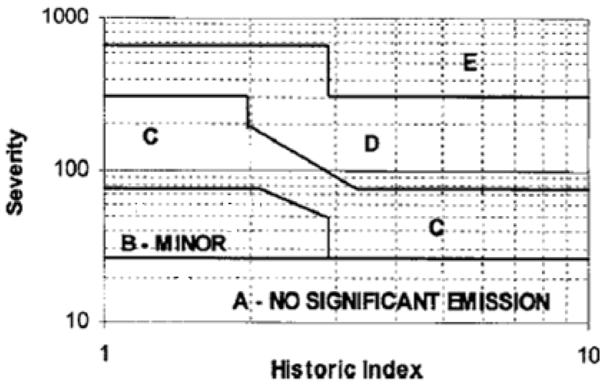


FIGURE 04: Typical intensity chart for metal piping system (Gostautas et al., 2005)

3 WORK AT QUT

The current work at QUT is targeting the three issues discussed in Section 2.2. All three involve investigation for intelligent data processing tools to achieve effective monitoring system. A brief overview of the work currently undertaken is presented next.

3.1 Source location

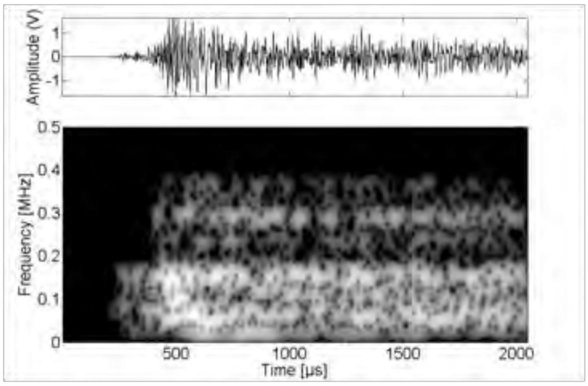
Accurately locating source is one of advantages of AE technique but is challenging. To identify wave modes and study source location, experiments were carried out in a steel plate, which formed the deck of a slab-on-girder bridge model, and had dimensions of 1.8 m by 1.2 m and thickness of 3 mm. AE data acquisition system used for experimentation was µ-disp PAC (Physical Acoustics Corporation) system with four channels, with three R15α sensors (made by PAC, resonant at 150 KHz). AE signals were generated by breaking 0.5 mm pencil leads at selected locations on the plate. Breaking pencil leads on a surface has been found to generate crack like signals, so are often used as sources of acoustic emission in experiments and in sensor calibration (Prosser, 2002). Plate-like structures are common in various applications, hence were used as experimental specimen.

Further experimental details and elaborate results from data analysis can be found in Kaphle, Tan, Thambiratnam and Chan (2010). To summarize, the study showed that the analysis of recorded AE waveforms, by means of time-frequency signal processing techniques, helped in identification of wave modes which in turn helped in accurate source location. Identification of modes becomes more significant when some modes may be lost among the noises with increasing sensor to source distance.

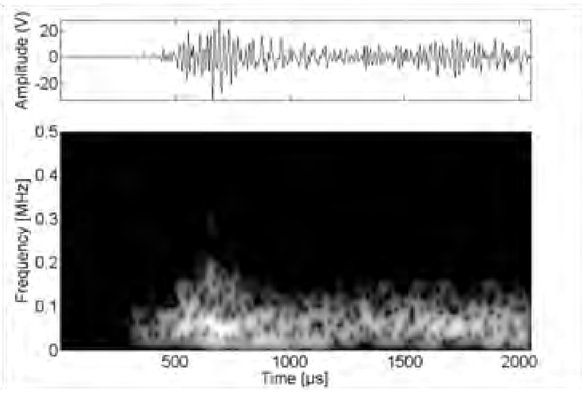
3.2 Source differentiation

Two sources of AE signals were generated by (a) breaking 0.5 mm pencil leads (Hsu-Nielsen source) and (b) dropping steel balls (6 mm diameter) from a height of 15 cm on a 4 m long steel beam. Ten sets of each test were carried out. Four channel µ-disp PAC system along with two PAC R15α sensors placed at distances of 1.5 m (named Sensor S1) and 3 m (named Sensor S2) from the source were used for data acquisition. The sensors were coupled to the test specimen using vacuum grease and magnetic holders. For each hit, data was acquired at a sampling rate of 1 MHz (one sample per 1 µs) and recorded for duration of 15 ms. Signals recorded were then analysed, first by calculating energy distributions in different frequency bands from STFT analysis. Then, cross-correlation coefficient and magnitude squared coherence were calculated using Matlab commands ‗xcorr' and ‗mscohere' to check signal similarity in time and frequency domains respectively. The command ‗xcorr' gives the value of 1 for two identical signals. Similarly, ‗mscohere' gives values lying between 0 and 1 which indicate how well two signals correspond to each other at each frequency; with the value of 1 indicating exact match (MathWorks Inc., 2009).

Time-frequency spectra of a pencil lead break (PLB) and a ball drop (BD) signal recorded by sensor S1 calculated using Time-frequency toolbox (Auger, Flandrin, Goncalves, & Lemoine, 1996) are shown in Fig. 05 below (squared STFT coefficients are shown representing energy).



(a)



(b)

FIGURE 05: Signals (upper) along with STFT representation (below): (a) PLB, and (b) BD

Then, frequencies between 0 till 500 KHz were divided into eight equally spaced bands and energy distribution in these bands was calculated as the ratios of the total energy. It was found that that for BD signals most energy (74-79%) lie in frequencies less than 62.5 KHz while almost no energy lies above 125 KHz. For PLB signals, energies are distributed pretty equally between then bands 0-62.5 KHz, 62.5-125 KHz and 125-187.5 KHz. Hence this distinct distribution of energy in different bands can act as a suitable guide for source differentiation.

While performing cross-correlation of the first PLB signal with remaining nine PLB tests, an average maximum value of 0.87 (in the range between 0.80 and 0.91) was obtained while that for cross-correlation between the PLB with 10 BD signals was 0.48 (in the range between 0.38 and 0.54). Similarly, the mean MSC values of first PLB signal with the rest PLB signals lie in the range 0.71 – 0.75, while mean MSC values of the PLB signal with other ten ball drop signals recorded lie in the much smaller range of 0.25 – 0.35 with a mean value of 0.29. The distinct difference in values indicates the suitability of these methods for signal discrimination.

3.3 **Severity assessment**

A number of previous studies have attempted to quantify damage in concrete structures using AE, but studies on steel structures are limited. Hence the aim of this work is to test the above two quantification methods for applications in steel structures.

For preliminary study, three point bending test was carried to simulate cracking on a 300 mm long, 25 mm by 25 mm square cross-sectioned steel piece with a 15 mm notch cut through it, see Fig. 06. INSTRON tensile machine with 100 KN load-cell was used to apply loads to the specimen at a loading rate of 1 mm/min. Same data acquisition system as previous was used for AE data acquisition. Sensors were placed at the ends of the beam, equidistant from the crack to record AE signals from growing crack. Both b-value analysis and intensity analysis were then performed.

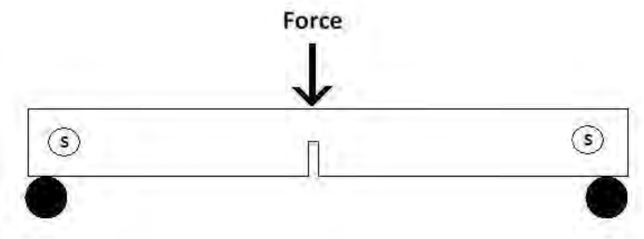
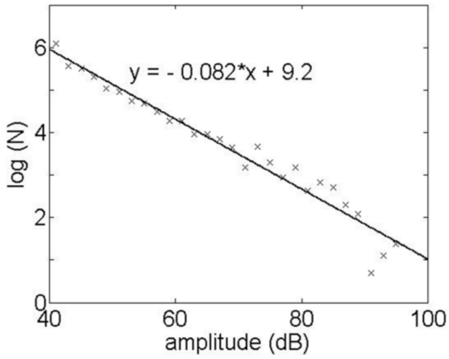


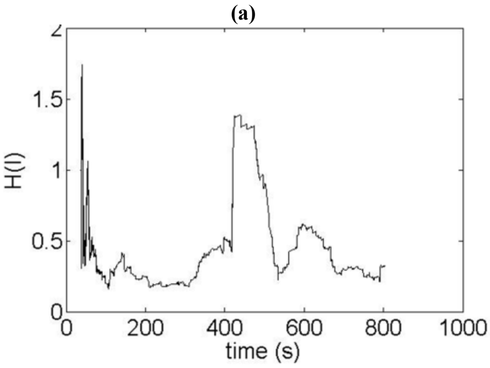
FIGURE 06: Three point bending test

Some preliminary results are shown in Fig. 07. From b-value analysis (Fig. 07a), it is seen that number of events (in logarithmic scale) and amplitude range vary linearly and b-value of 1.64 is seen (20 times the slope of 0.082). By testing concrete specimens and performing b-value analysis in different stages, Carpentri et al. (2009) have found the b-values to lie between 1.5 and 1. The values for steel, however, have not been quoted in literature, so more experiments and data analysis will be needed to confirm the values for steel specimens.

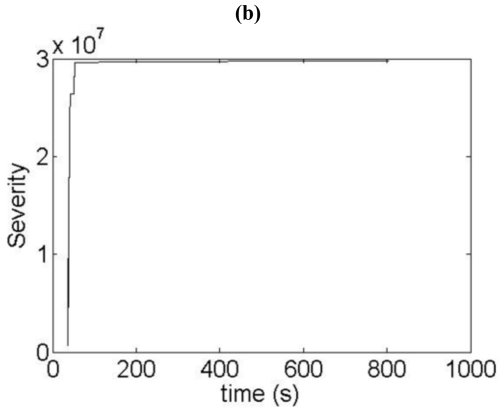
For intensity analysis, historic and severity indices were plotted against time (shown in Figs. 07b & 07c respectively). The maximum values of historic and severity indices are seen to be 1.75 and 3 x 10^7. When plotted against each other and compared with the intensity chart used for metal piping industry (Fig. 04), the value is seen to lie in the region E of the chart (though well outside the ranges shown in the chart). Since actual crack growth increased in this test and the specimen nearly failed, position in this region proves that this is major defect. Similar high values were seen in studies in glass fibre-reinforced composites by Gostautas et al. (2005), who also state the trend of intensity values of high structural significance occurring toward the top right-hand corner of the chart and values of less significance near the bottom left.



(a)



(b)



(c)

FIGURE 07: b-value analysis (a) and intensity analysis showing historic (b) and severity (c) indices with time

More tests will also be carried out in future with different loading rates to test the behaviour at different intensity loads and to attempt to develop some guidelines (b-value and intensity chart).

4 CONCLUSIONS

In conclusion, three important aspects of acoustic emission testing, namely source location, source identification/discrimination and severity assessment, were discussed in this study. All three require innovative and intelligent use of several signal processing tools combined with the study of AE signal parameters and their statistical distribution. This combination will also provide efficient way to process large volumes of data generated, which is a vital area of ongoing research in the field of acoustic emission testing. Summary of the work currently carried out at the university was also presented. Future work will also study application of these tools for real life monitoring applications.

5 ACKNOWLEDGEMENTS

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